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# DEVELOPMENT OF
# MILLIMETER AND SUBMILLIMETER MASER DEVICES

Interim Technical Report No. 1

1 February 1963 to 31 May 1963

Contract No. AF-33(657)10472
Task No. 415604

Prepared by

Mr. W.E. Hughes
WESTINGHOUSE ELECTRIC CORPORATION
Air Arm Division
Applied Physics Group
Baltimore, Maryland





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# FOREWORD

This document is the first triannual report which discusses the work accomplished in a millimeter and submillimeter maser program conducted from 1 February 1963 to 31 May 1963 by the Air Arm Division of the Westinghouse Electric Corporation under Air Force Contract AF-33(657)10472. The program is under the direction of Mr. R.E. Deal of Electronic Technology Laboratory of the Aeronautical Systems Division, Wright Field.

The Westinghouse personnel associated with this program are Mr. W.E. Hughes, Mr. W.E. Richards, Dr. R.A. Moore, and Mr. D.C. Webb of the Air Arm Applied Physics Group. Dr. J.G. Castle of the Westinghouse Research Laboratories and Dr. P.E. Wagner of The Johns Hopkins University are acting as consultants for this particular program.

## ABSTRACT

The first reporting period under Contract AF-33(657)10472 has been devoted to establishing possible maser pumping schemes and obtaining instrumentation for experiments at frequencies near 140 gc.

Tests were made, using the iron ion in rutile as active material, to determine if maser action could be expected at the proper frequency. The tests were encouraging; however, maser amplification could not be shown because there were no signal sources on hand.

A sample of iron-doped zinc tungstate was obtained and tested; however, it does not appear to offer any significant advantage for millimeter maser development over iron-doped rutile.

The IBM 7090 computer facility at Air Arm has been programmed to obtain transition probabilities for iron-doped rutile. These transition probabilities are necessary in order to understand more easily the operation of millimeter wave masers. To date only the simple 3-level type maser has been investigated, but analysis of the more complicated 5-level maser will be attempted soon.

## LIST OF SYMBOLS

$\omega_{ij}$ = Spin-lattice transition probability between $i^{th}$ and $j^{th}$ energy levels

$T$ = Temperature, degrees Kelvin

$h$ = Planck's constant

$k$ = Boltzmann's constant

$n_i$ = Population density of $i^{th}$ level

$N$ = Population density of entire system

$\nu_{ij}$ = Transition frequency between $i^{th}$ and $j^{th}$ levels

$W_{ij}$ = Radiation induced transition probability between $i^{th}$ and $j^{th}$ energy levels

$\theta$ = Angle between dc magnetic field and Z axis

$\phi$ = Angle between projection of dc magnetic field on X-Y plane and X axis

$H$ = Magnitude of dc magnetic field

$\mathcal{H}$ = Hamiltonian

gc = $10^9$ cycles per second (gigacycle)

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## 1. INTRODUCTION

The purpose of Contract AF-33(657)10472 is to carry out an investigation of millimeter and submillimeter wave masers. The program is to extend the state of the art for maser amplifiers, specifically in the area of new pumping techniques. These techniques are to be investigated in the 140- to 300-gc range which will allow operating frequencies higher than the pump frequency.

The iron ion in a host crystalline structure is being used as the active material for the 140-gc operation. Several tentative operating points have been chosen for operation. However, since a signal source at 140 gc was not available during this period, definite maser operation was not established.

In order that the new pumping techniques can be more easily selected, a computer program has been established to help determine transition probabilities between the various energy levels of iron-doped rutile. It is anticipated that the solutions obtained will allow a better theoretical understanding of the multilevel pumping techniques.

Since it is expected that in future maser programs it may be necessary to operate the devices at temperatures above liquid helium temperatures, the spin-lattice relaxation times for iron in rutile have been measured as a function of temperature at X-band frequencies up to 20° Kelvin. The measurements indicate that the relaxation times are linear functions of temperatures from 4.2° to 20° Kelvin; thus, to operate the masers at higher temperatures, the pump power necessary for inversion will need to be increased in a linear fashion. Although the measurements were made at only 10 gc, extention to higher frequencies should be possible.

Extension of the maser operating frequency to near 300 gc will require that some active material other than iron-doped rutile be used if reasonable

dc magnetic fields (under 10 kilogauss) are to be maintained. The new materials which show promise are iron-doped zinc tungstate, iron-doped yttrium oxide, and cerium in lanthanum ethyl sulfate. Of these materials only the iron-doped zinc tungstate has been received to date, and tests show that the zero field splitting is not great enough to be useful. Therefore, attempts to obtain the other two materials are being made.

# 2. MATERIAL INVESTIGATION

## 2.1 EXPERIMENTAL INVESTIGATION OF RUTILE

For the iron ion ($Fe^{3+}$) in rutile ($TiO_2$) there appears to be a wide variation in the relaxation times between the spin energy levels; thus, if care is used in selecting maser pumping and signal transistions, it is possible to obtain inversion between levels which are separated by frequencies greater than the pump frequency transitions. Therefore, amplification at a frequency higher than the pump frequency is possible. This type operation was shown on Contract AF-33(616)7202 in which three levels were simultaneously pumped at a frequency of 65.2 gc and amplification was obtained at a frequency of 96.3 gc. The spin energy level diagram for that type operation is shown in figure 1 with a typical arrangement of energy levels being shown in figure 2.

The five-level maser operated very well; however, the requirement of pumping three levels simultaneously made it difficult to operate. Therefore, it was decided that a different type pumping scheme might be beneficial.

It has been suggested several years ago by Dr. P. E. Wagner that, if a proper relation between relaxation rates in maser systems could be obtained, then amplification at a signal frequency higher than the pump frequency would be possible.[1/] That is, if the energy levels are arranged as shown in figure 2, then it may be possible to obtain amplification at a frequency higher than the pump frequency. An experiment was conducted in which the spin energy levels of the iron ion in rutile were arranged as shown in figure 3. At a temperature of 2° Kelvin it was possible to invert the populations between levels 5 and 2 and obtain a small amount of amplification. Figure 4 is a photograph of the amount of electronic gain that was achieved, where the top photo is the output

1. Quarterly Technical Report #10, Maser Studies Part 1, Task 50899, Project 4144, Research Report AF-33(616)5258-R10. 15 August to 15 November 1959, 6.

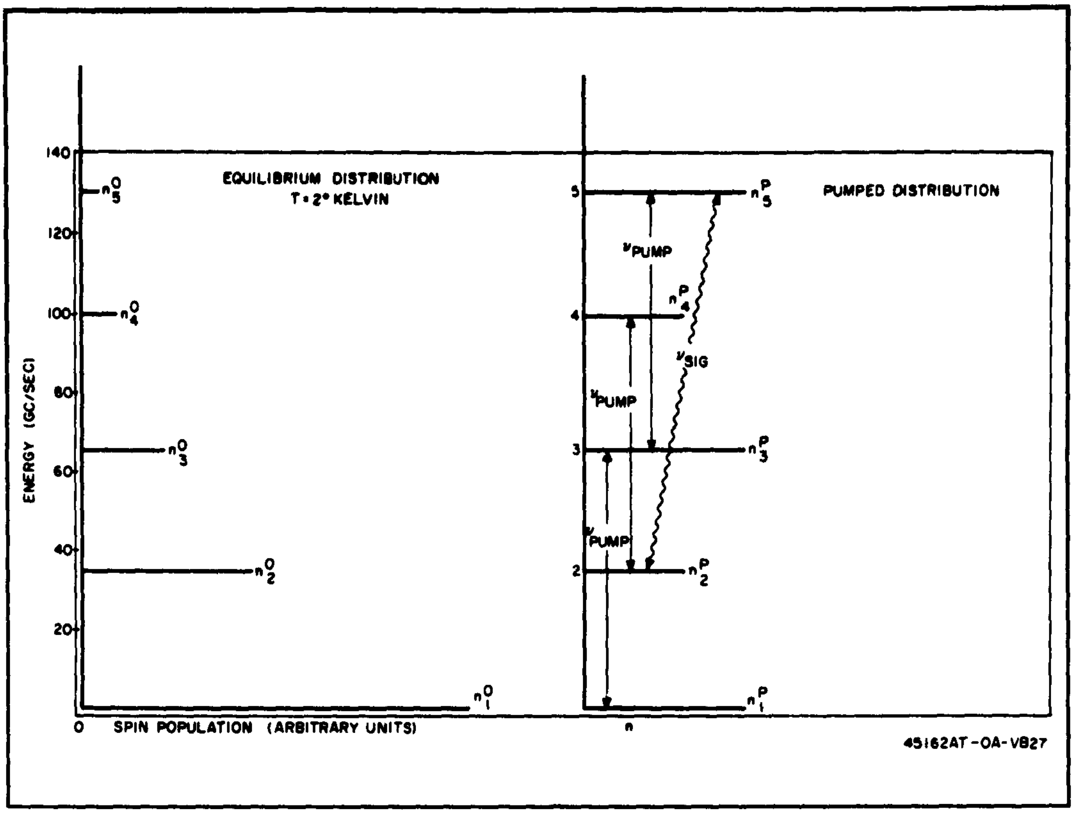


Figure 1. Spin Distribution for 5-Level Maser

signal with pump off and the bottom photograph is the output signal with pump energy on.

Since the present contract is concerned with masers operating in the frequency range of 140 gc, it was decided to try the alternate pumping scheme for this operation. The energy levels of the iron ion were arranged in a manner similar to that in figure 3, except the pump energy was applied between levels 1-4 and 4-6 at a frequency of 100.5 gc; attempts were made to show that levels 6-3 were inverted at a frequency of 148 gc. Since no signal source was available at the proper frequency, it was not possible to show definitely that maser action was possible. However, there were strong oscillations occurring at a frequency of about 48 gc indicating that the 4-3 level is inverted; thus, if the population in level 6 is equal to that in level 4,

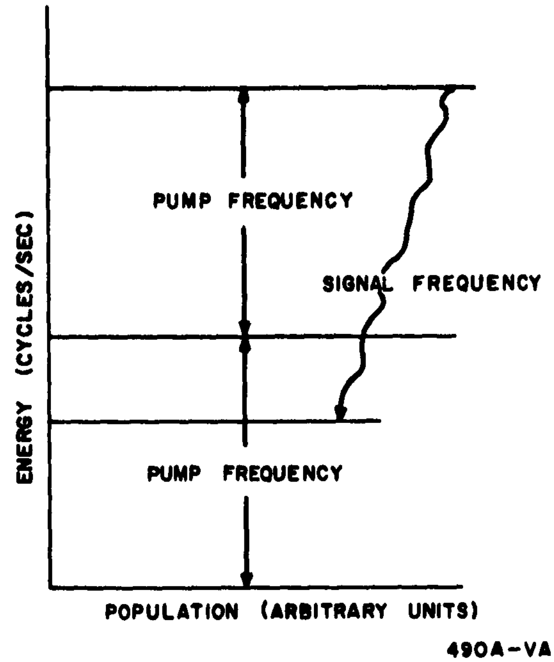


Figure 2. Energy Level Arrangement for Alternate Pumping Scheme

i.e., pump saturation, then the 6-3 level should also be inverted. This operation will be checked as soon as a signal source can be obtained.

## 2.2 THEORETICAL INVESTIGATION OF RUTILE

In the design of millimeter wave masers, a very critical parameter is the transition probability between energy states. In order to obtain an exact figure for this parameter it is necessary to use very precise, experimental methods. However, it is possible to estimate theoretically the transition probabilities from the properties of the appropriate spin Hamiltonian. The process for this approach is as follows.

The spin Hamiltonian in the form of a determinant is diagonalized to obtain the eigen values or energy levels. These eigen values are then substituted back into the determinant, and solutions for the eigen vectors are obtained.

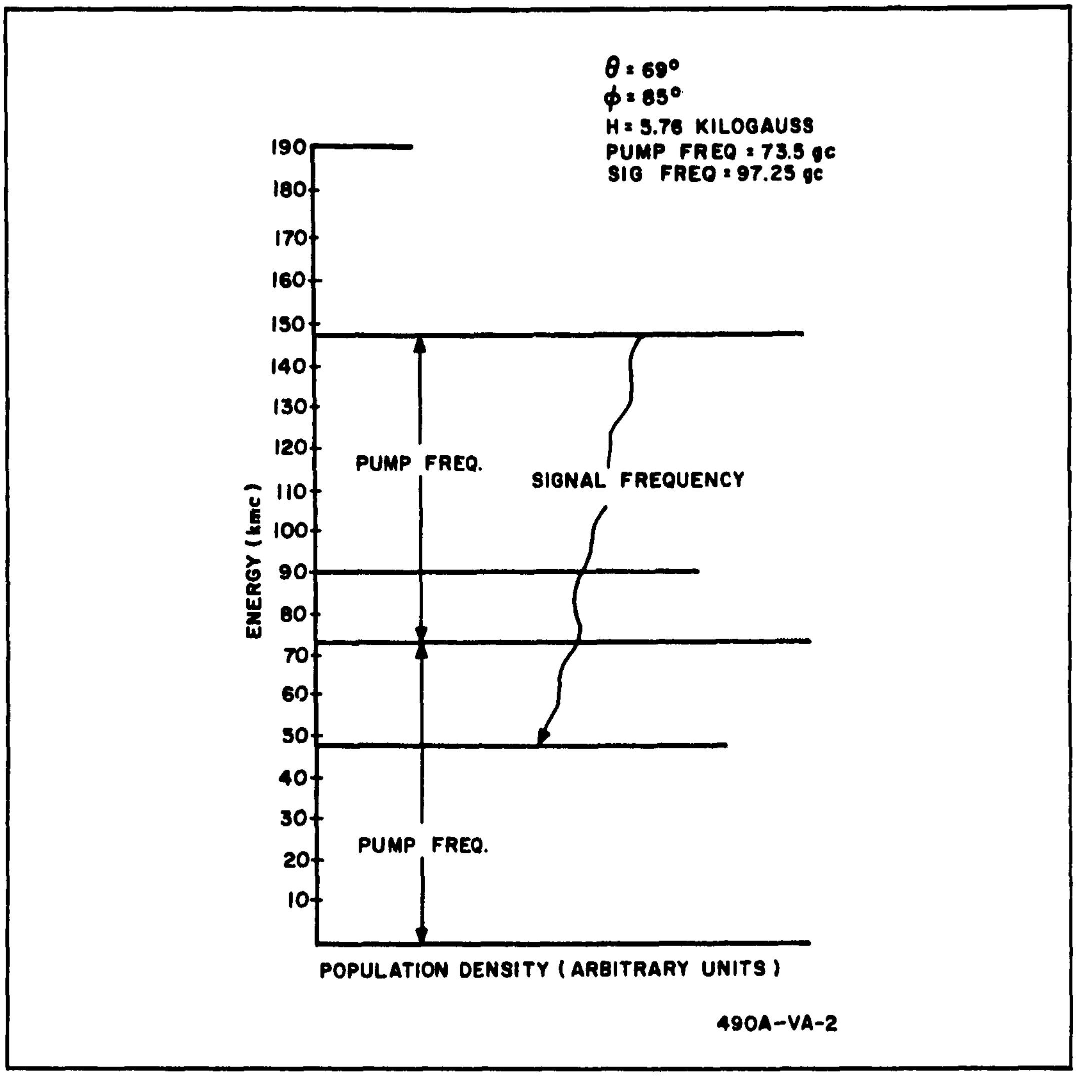


Figure 3. Energy Level Distribution of Iron in Rutile for Alternate Maser Pumping Scheme

The eigen vector operators are then used in conjunction with a new Hamiltonian to determine the transition probabilities. The theoretical consideration can give only approximate transition probabilities because of the unknown effect of crystalline host inperfections, impurity concentrations, exact field configurations, and various coupling parameters. To date very little has

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Figure 4. Maser Output Signal for Alternate Pumping Scheme

been done to determine experimentally the exact transition probabilities for the particular situations encountered in this program.

## 2.3 ZINC TUNGSTATE INVESTIGATION

During this period a sample of zinc tungstate, Zn $WO_4$, doped with iron ions, $Fe^{3+}$, was received from the National Lead Company. The tungstate was obtained so that the zero field splitting could be determined with the intent of using it as a millimeter wave maser material.

Preliminary measurements indicated that the zero field splittings were near 62 gc and 80 gc. However, communication with Dr. S.K. Kurtz of the Bell Telephone Laboratories disclosed that he was making a thorough study of this material; thus, our experiments were discontinued to avoid duplication of effort. Dr. Kurtz has agreed to forward his experimental data to us as it becomes available.

## 2.4 LANTHANUM ETHYL SULFATE

In a search for promising millimeter wave maser materials one of the first requirements of the material is that it have a very high zero field splitting. This requirement is necessary in order that high energy level separation can be achieved with reasonable dc magnetic fields.

The $Ce^{3+}$ ion in a host crystal of $La(C_2H_5SO_4) \cdot 9H_2O$ has a zero field splitting of about 118 gc;[2] therefore, it appears as a good possible maser material. Samples of this material are not easily available; however, they can be grown from solution, and the necessary materials have been ordered with delivery expected soon. When the powders arrive, attempts to grow suitable single crystals will be made.

2. Devor and Hoskins, Bulletin of The American Physical Society, Series II, Vol. 6, No. 4, (1961), 364.

## 3. TEST FACILITY

The maser test facility to be established at Wright Field is progressing as expected. All of the major items have been ordered, and with the exception of the electromagnet most of the components are on hand. A 300-gc signal source has been ordered with delivery expected in approximately 5 months.

## 4. IDENTIFICATION OF PERSONNEL

A list of the personnel, their titles, and the approximate number of man-hours performed by each one during the period covered by this report are given below.

| Name | Title | Man-Hours (percent) |
|---|---|---|
| Wayne E. Hughes | Project Manager | 75 |
| W.E. Richards | Assistant Engineer | 30 |
| Denis C. Webb | Engineer | 20 |
| Robert A. Moore | Fellow Engineer | 10 |
| J.G. Castle, Jr. | Consultant | 10 |
| P.E. Wagner | Consultant | 5 |

| | | |
|---|---|---|
| NAME: | Wayne E. Hughes, Project Manager | |
| EDUCATION: | A. B., Physics, Gannon College, 1956<br>Graduate Courses, University of Maryland | |
| EXPERIENCE: | 1956 - 1957 | Bliley Electric Company, Erie, Pennsylvania. Engaged in design and testing of solid ultrasonic delay lines. |
| | 1957 - Present | Westinghouse Electric Corporation, Air Arm Division, Baltimore, Maryland. |
| | 1957 - 1959 | Engineer, engaged in design and development of components of a matched-filter airborne radar system. |
| | 1959 - 1961 | Engaged in the laboratory development of maser amplifier in the millimeter-wavelength region. |
| | 1961 - Present | Project Engineer, millimeter wave maser studies. Broadband millimeter wave maser. |
| PATENTS: | Five-Level Maser Pumping Technique<br>Six patent disclosures in the field of maser devices. | |
| SOCIETIES: | American Physical Society | |

| | | |
|---|---|---|
| NAME: | William E. Richards, Assistant Engineer, Applied Physics Group | |
| EDUCATION: | B. S., Engineering, Physics, University of Maine, 1962 | |
| EXPERIENCE: | 1954 - 1958 | U.S. Air Force |
| | 1960 - 1961 | Maine Public Service Company |
| | 1962 - Present | Westinghouse Electric Corporation. Graduate Student Program. Short term assignments included piezoelectric generators, varactor analyses, and parameter control, and studies on the temperature dependence of the conductivity of $TiO_2$. Applied Physics Group. Concerned with millimeter wave maser analysis and detector studies. |
| SOCIETIES: | Sigma Pi Sigma | |

| | | | |
|---|---|---|---|
| NAME: | Denis C. Webb, Engineer | | |
| EDUCATION: | B. S., Engineering Physics, University of Michigan, 1960<br>M. S., Physics, University of Michigan, 1961 | | |
| EXPERIENCE: | 1960 | Union Carbide Corporation. X-ray studies of refractive materials. | |
| | 1961 - Present | Westinghouse Electric Corporation. Graduate Student Training Program. Studies on antiferromagnetic materials, thin films, and semiconductor materials. Applied Physics Group, Air Arm Division. Study of ferrimagnetic and maser traveling wave structures. | |
| SOCIETIES: | Tau Beta Phi<br>Institute of Electrical and Electronics Engineers | | |

| | | | |
|---|---|---|---|
| NAME: | Robert A. Moore, Fellow Engineer | | |
| EDUCATION: | B. S. E. E., University of Alabama, 1954<br>M. S. E. E., Northwestern University, 1958<br>Ph. D. E. E., Northwestern University, 1960 | | |
| EXPERIENCE: | 1954 - 1958 | Northwestern University - Graduate Assistant and part-time instructor. | |
| | 1958 - 1959 | United States Army. Signal Corps<br>Three months - Officers Basic Signal Course<br>Three months - USASRDL (Evans Area)<br>Study of applications of gyromagnetic materials to microwave circuitry. | |
| | 1958 - Present | Westinghouse Electric Corporation (except six months active duty with Army) Electronics Division - Conducted studies of ionospheric and tropospheric electromagnetic propagation for application to advanced radar techniques. Air Arm Division. Applied research directed toward the investigation of the steady-state and transient responses of nonlinear, nonisotropic materials such as ferrimagnetic for microwave and millimeter wave applications. Electromagnetic mode propagation on structure of these materials has been investigated for traveling-wave applications such as filtering and paramagnetic amplification at millimeter waves. | |

PUBLICATIONS:

"A Duo-Dielectric Parallel-Plane Waveguide," Proc. NEC, 1946.

"Ferrite Post Microwave Resonant Structure," Winter Convention on Military Electronics," with W.J. Parris.

"Leakage Characteristics of a Microwave Ferrimagnetic Power Limited," Winter Convention on Mil. Elec., with J.L. Carter and Irving Reingold.

"Microwave Ferrite Filter and Power Limiter," IRE International Conference, with J.L. Carter and Irving Reingold.

"Millimeter Wave Parametric Amplification with Antiferromagnetic Materials," Seventh Annual Conf. on Mag. and Magnetic Mat., Proc. in Special Issue of J.A.P.

| | |
|---|---|
| NAME: | Robert A. Moore (Continued) |
| SOCIETIES: | Institute of Electrical and Electronics Engineers<br>American Physical Society<br>Tau Beta Pi<br>Eta Kappa Nu<br>Sigma Xi<br>Phi Eta Sigma<br>Sigma Pi Sigma |

NAME: J.G. Castle, Jr. (Consultant), Section Manager, Physics Department, Research Laboratories

EDUCATION: B.A., Physics and Mathematics, University of Buffalo, 1947
Ph.D., Physics, Yale University, 1950

EXPERIENCE: 1950 - Present Westinghouse Electric Corporation, Research Laboratories, Pittsburgh, Pennsylvania. Nine years in research and development in the field of microwave spectroscopy, cryogenic design, and materials preparation techniques. Specific devices applicable to molecular amplifiers include helium liquifier, maser amplifier storage display tube, nonlinear capacitors using ferroelectrics, and paramagnetic relaxation time measurements of single-crystal materials suitable for solid state masers.

PATENTS: Various patents and 23 disclosures in the field of molecular devices.

PUBLICATIONS: Publications related to molecular amplifiers:

"Magnetic Resonance Absorption in Nitric Oxide," Physics Rev. (1949 and 1950)

"Microwave Magnetic Resonance Absorption in Oxygen," Physics Rev. (1951 and 1949)

"Microwave Magnetic Resonance Absorption in Nitrogen Dioxide," Physics Rev. (1950)

"Paramagnetic Resonance Absorption in Graphite," Physics Rev. (1953)

"Magnetic Resonance Properties of Raw Cokes," Bull. Am. Phys. Soc. (1955)

"Two-Level Solid State Maser," Physics Rev. (1958)

"Magnetic Resonance Absorption in Carbon Black," Proc. of Third Carbon Conf. (1958)

Additional articles as coauthor with P. E. Wagner

SOCIETIES: Phi Beta Kappa
Sigma Xi
American Physical Society

| | | |
|---|---|---|
| NAME: | P. E. Wagner, Professor, The Johns Hopkins University | |
| EDUCATION: | Ph. D., Physics | |
| EXPERIENCE: | 1953 - 1959 | Westinghouse Research Laboratories, Research Physicist. Detailed studies on masers and basic research in paramagnetic crystal properties. |
| | 1959 - Present | The Johns Hopkins University. Professor, Electrical Engineering Department. Theoretical quantum electronics. |

## 5. CONCLUSIONS AND RECOMMENDATIONS

Although it was not possible during this period to show definite maser amplification at 140 gc due to the lack of a suitable signal source, the experiments that were conducted gave encouraging results. It was demonstrated that inversion of the proper spin energy levels might be achieved using pumping techniques developed on previous programs. It was also shown that a better understanding of spin-lattice relaxation processes is essential to the design of millimeter and submillimeter wave masers. This understanding can be obtained by a thorough study of the particular materials and energy levels being considered.

It was determined during this period that in order to fabricate a 300-gc maser operating in the 5-level pumping configuration it will be necessary to obtain a new active material or to use much higher magnetic fields. Which of these two solutions will prove to be the most feasible has not yet been decided.

One problem area of the millimeter and submillimeter region that has been revealed on this program is that of obtaining very sensitive and fast operating detector devices. Although point contact diodes have been operated in this frequency range, their operations are marginal; a program to study detectors in this range would be useful. Since this type of development is not within the scope of the present program, perhaps a separate program would be beneficial.